National-scale infrastructure network exposure assessment using geospatial liquefaction tools

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ABSTRACT

Liquefaction hazard maps are a useful tool to help estimate the exposure and potential liquefaction-induced damage to the built environment. The most robust approach for the development of these maps is through the use of in-situ investigation data and simplified liquefaction evaluation procedures. When infrastructure networks are the focus of assessment, this method can be expensive and labour-intensive due to the geospatial extent of these networks and the large number of investigation data required to provide good coverage. In these cases, geospatial methods can be used as an alternative approach. This paper focusses on the assessment of the exposure of New Zealand's transportation and power transmission networks to liquefaction, using geospatial liquefaction susceptibility methods. This approach enabled the initial quantification of the overall national exposure across each network for different liquefaction susceptibility categories, demonstrating that transportation systems – rail, state highways, and bridges – are situated across regions that are more susceptible to liquefaction in comparison to power transmission facilities. To identify areas of high risk in terms of liquefaction induced damage, susceptibility needs to be linked with the seismic hazard across the country, this is the focus of the next step of this research. The criticality or significance of infrastructure should also be considered as part of this process to better quantify the impact of damage to the wider economy and society. This includes the modelling of other infrastructure networks, such as local roads, and the analysis of links between networks and areas of interest, such as populated places and sea ports.

Keywords: liquefaction, geospatial methods, infrastructure, New Zealand

1 INTRODUCTION

Liquefaction during seismic events can lead to significant damage to buildings and infrastructure networks, including differential settlement of buildings, distortion of roads, or breakage of buried infrastructure (Mian et al., 2013). Because of its young coastal sediments and its location along the Pacific Basin Ring of Fire, New Zealand is prone to liquefaction induced damage. During the 2010-2011 earthquakes in Christchurch, liquefaction and lateral spreading led to significant damage to the built environment; it affected around 60 000 residential houses and severely impacted lifelines and infrastructure within the city (Cubrinovski, 2013).

An effective tool to identify areas of risk and to estimate the potential extent of damage to buildings and infrastructure is a liquefaction hazard map. However, the development usually requires extensive investigation to characterise the potential liquefaction-induced damage using simplified liquefaction evaluation procedures. Common in-situ site investigation methods to obtain this information are the Standard Penetration Test (SPT) or Cone Penetration Test (CPT) (Boulanger & Idriss, 2014; Zhu et al. 2017). When assessing distributed infrastructure networks, the number of investigations required can be expensive and labour-intensive, hence they may not be suitable for the overall assessment of large-scale networks.

In this case, geospatial methods can be used as an alternative approach. Zhu et al. (2015) developed and updated (Zhu et al., 2017) a liquefaction model based on geospatial characteristics, such as slope, elevation or distance to a water body. As the aim to this approach was the creation of a tool for rapid estimation of the extent of liquefaction in order to support rapid response and emergency planning, only variables which were easily accessible prior to any event were considered.

This paper focuses on the application of geospatial liquefaction susceptibility models for New Zealand to assess the exposure of national infrastructure networks. Here we focus on state highways, rail and the power transmission network. The paper also compares specific examples of infrastructure systems to evaluate contributing factors such as earthquake likelihood and infrastructure criticality.

2 GEOSPATIAL LIQUEFACTION MODEL

The Zhu et al. geospatial liquefaction model relies on a set of 18 variables which are related to factors most relevant to liquefaction: soil properties (relative density), water table depth (saturation), and ground shaking (load). To correlate these variables with liquefaction occurrence, case history data from 22 different earthquakes in the United States, Japan, New Zealand and Asia were obtained. Five events where liquefaction did not manifest within the same areas were also assessed to account for low intensity shaking events, in which liquefaction is unlikely to occur. The consideration of both scenarios maintained the data's completeness and increased the accuracy of the model. Since most liquefaction has manifested in coastal areas, the primary model was biased, making it less applicable to non-coastal regions. Therefore, a modified model with a different arrangement of variables was introduced for global implementation (Zhu et al., 2015; Zhu et al., 2017).

For soil properties and saturation, the best-performing variables were *slope-derived* V_S30 (shear-wave velocity over the first 30 m), *water table depth*, *distance to coast*, *distance to river*, *distance to closest water body*, and *precipitation*. *Peak ground velocity* (PGV) proved to be most suitable for characterizing ground shaking intensity. Interaction effects among variables, e. g. between *distance to coast* and *distance to rivers*, were also considered and improved the overall performance of the model. (Zhu et al., 2017)

Using logic regression, liquefaction probability was estimated and mapped for all events from the dataset. Comparing the predictions of both models with the actual observations showed several discrepancies, revealing the limitations of the approach. One reason for inaccurate results was the fact that site specific characteristics and other contributing factors (e. g. soil plasticity) were not included due to their restricted accessibility. Beyond that, the global model did not perform as well as the regional (coastal) model, indicating that variables related to soil saturation were the driving factor for liquefaction occurrence. Despite its limitations, the model of Zhu et al. (2017) provides useful results, especially considering the cost and time required to collate traditional in-situ methods across such a broad area (Maurer, 2017). It is therefore the best tool for assessment of liquefaction on a national scale and to estimate the potential liquefaction-induced damage to New Zealand infrastructure networks.

Based on the global model, a susceptibility map of New Zealand at a 100 m grid spacing was created (Fig. 1). Instead of the global Vs30 model, this approach made use of a recently developed New Zealand-specific V_S30 model (currently unpublished). Following the classification of Zhu et al. (2017), the susceptibility data can be interpreted by introducing the categories very low (white), low (green), moderate (yellow), high (orange),

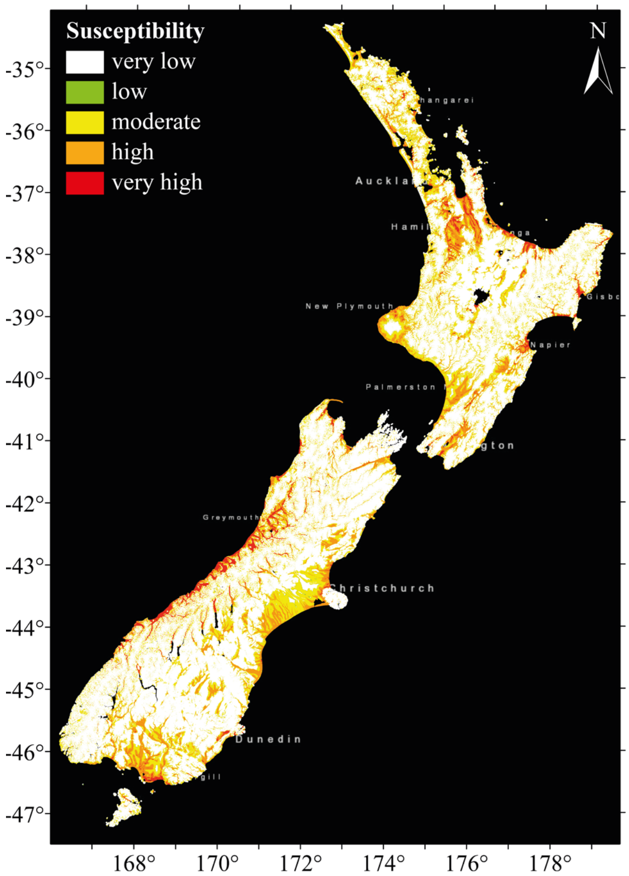

Fig. 1 Liquefaction susceptibility map of New Zealand based on the geospatial model of Zhu et al. (2017)

and very high (red). The map shows areas of high susceptibility in the centre of the North Island (Waikato, Bay of Plenty) and along the West coast of the South Island. These are areas with a lack of site specific investigation data, and also align with areas where the liquefaction susceptibility of deposits is the focus of current research (Tauranga City Council, 2016; Wahab & Clayton, 2017). As such, according to this geospatial model, the infrastructure in these districts may be exposed to liquefaction effects, and will be the focus of further analysis in this paper.

3 INFRASTRUCTURE NETWORKS

The functionality of national infrastructure networks is essential to provide services such as transportation and power transmission. Because of their geographic distribution, they are exposed to a range of natural hazards. In the event of an earthquake, liquefaction-induced lateral spreading and ground deformation are the main causes for infrastructure damage. The impact varies between surficial changes, which do not interfere with the network's functionality, and a total failure of the system (Mian et al., 2013; Ministry of Business, Innovation & Employment, 2017).

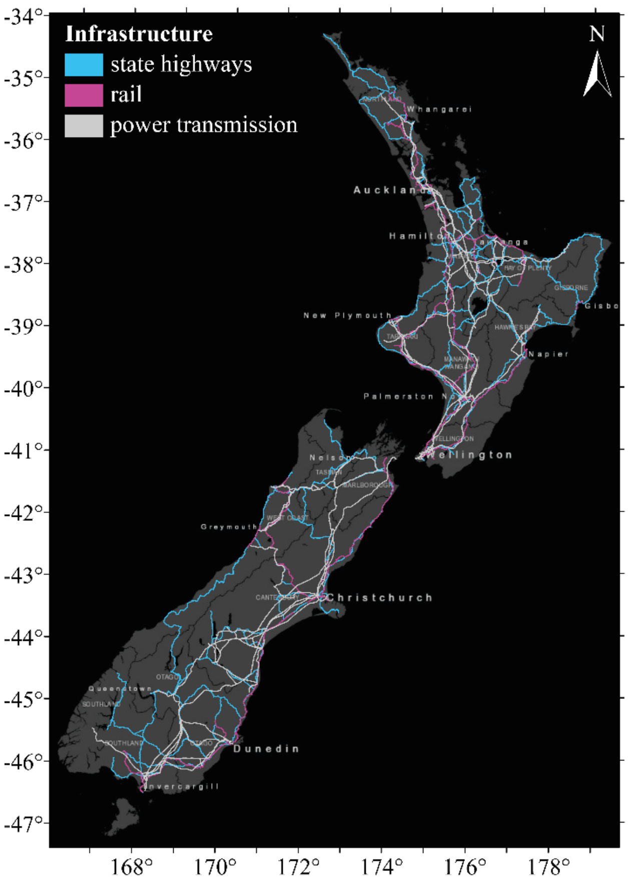

Fig. 2 Infrastructure networks of New Zealand

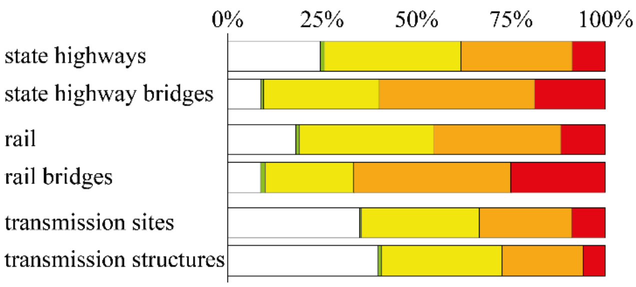

Fig. 3 Liquefaction susceptibility of New Zealand infrastructure

This paper analyses New Zealand state highways, rail network and the power transmission network (Fig. 2). State highways represent only 12 % of the entire road system, but account for up to 50 % of all motor vehicle travel distance. Facing a growing population, increasing freight transport and tourist travel needs, the state highways are a key network for New Zealand. Similar challenges apply to the rail network, which carries around 15 % of national freight and is predicted to experience a 70 %-increase of freight movement in the next two decades (Ministry of Transport, 2011). According to the New Zealand Lifelines Council (2017), most utilities are highly dependent on electricity, underlining the importance of the power transmission network. Although backup generators are very common to secure constant power supply, a large-scale outage would result in subsequent outages for many lifeline services.

To transfer infrastructure systems onto the liquefaction susceptibility map, publically available data sets from the NZ Transport Agency (state highways), Land Information New Zealand (rail, bridges) and Transpower New Zealand Limited (power transmission) was used. Following the data type of the susceptibility map, all infrastructure systems were modelled as point features. Linear networks were split into segments of 100 m, each represented by a centre point. In the assigning process, an infrastructure point simply adopted the value of the closest susceptibility point on the map.

Modelling the bridges of state highways and rail proved to be more complex: Since the data came in a polyline format as well, a triple of points was chosen to mark both ends (abutments) and the centre. The abutments are the most vulnerable part of the bridge; their susceptibility values determine the performance of the whole structure. The centre point, on the other hand, was chosen to illustrate the location more accurately on the map.

The power transmission network was characterised using the location of poles and pylons, as the functionality of the transmission lines are dependent on these structures. Locations of sites, representative of generation facilities and substations, were also assessed. A small overall length of subsurface cables are present in urban areas (e. g. Auckland), which are directly exposed to liquefaction (Transpower New Zealand Limited, 2018). For a detailed analysis on a local level, which goes beyond the scope of this paper, buried transmission lines should be taken into consideration.

4 SUSCEPTIBILITY ANALYSIS

Using the liquefaction susceptibility map for each infrastructure network, this section provides a short analysis, comparing the output and looking at two examples for further interpretation. An overview of the liquefaction susceptibility categories for all infrastructure types is shown in Fig. 3.

For state highways and rail, the results are very similar, which may be because rail follows the state highways at a number of locations (Fig. 2). The relatively high percentage of infrastructure sections with “moderate” to “very high” susceptibility (74.3 % for state highways, 80.9 % for rail) is because a large proportion of the networks are located close to the coast and across alluvial plain areas. For the assessment of liquefaction-induced damage, attention should be paid to areas where state highways and rail coexist, because it is very likely that both networks will be affected in the event of an earthquake.

Irrespective of the network, bridges lead to higher susceptibility results with 90 % of state highway bridges and 90 % of rail bridges being assigned a “moderate” to “very high” category. Bridges often span rivers, where

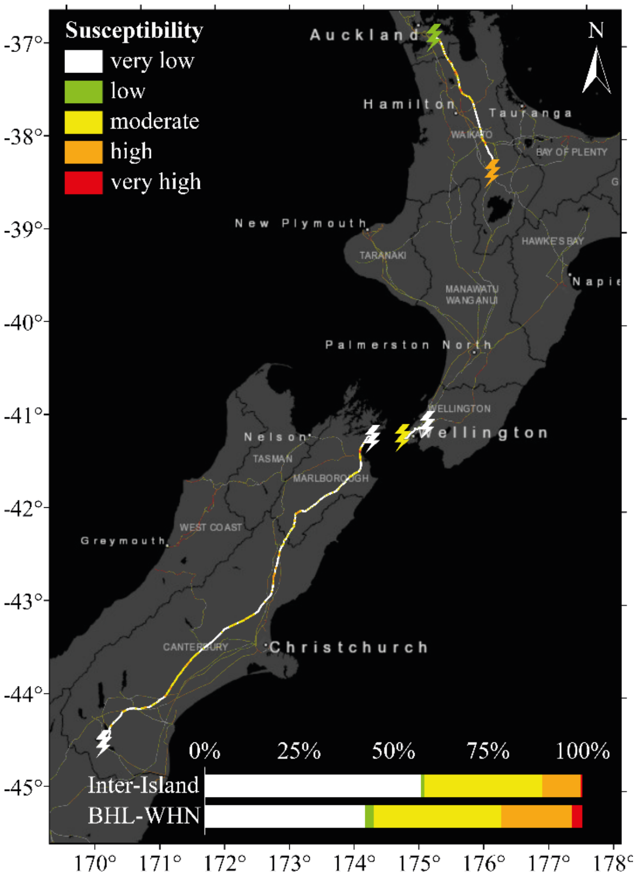

Fig. 4 Liquefaction susceptibility of the BHL-WHN line (North) and the Inter-Island line (South). The map shows both transmission sites and structures, while the chart only represents structures.

soil is alluvial and saturated, which is the primary indicator for liquefaction to occur (Youd, 1993). However, given the variability of soil deposit characteristics in these locations, further investigation would be necessary to confirm these classifications.

Power transmission sites and structures show significantly lower susceptibilities. One reason for this is the concentration of transmission structures on mountainous terrain and/or away from the coast, which decreases the exposure to liquefaction (but may increase the exposure to other hazards, such as landslides).

Using susceptibility maps allows an overall comparison of infrastructure networks. Future research could focus on adding other networks (e. g. local roads or water pipes) and analysing correlations among all components. Besides the general assessment on a national level, local hot spots could also be of interest.

4.1 Earthquake likelihood

High susceptibility does not necessarily result in high risk. Areas which are classified as very susceptible, but not prone to strong ground shaking, may be less relevant than areas of low susceptibility with a high exposure to earthquakes (Glassey & Heron, 2012). Zhu et al. (2017) assumed that a PGV of at least 3 cm/s is required to initiate the liquefaction process. To illustrate the importance of earthquake likelihood, two transmission lines will be discussed in detail (Fig. 4): (1) the BHL-WHN line between Brownhill (Auckland) and Whakamaru North (Waikato), one of the major high voltage alternating current lines in New Zealand, providing power to Waikato, Auckland and Northland; (2) the Inter-Island line, which starts in Haywards (Wellington) and crosses most parts of the South Island down to Benmore (Canterbury). The Inter-Island connects the power network of both islands and secures a balanced availability and demand ratio. It highly depends on the substation in Haywards, the main power supplier of Wellington (New Zealand Lifelines Council, 2017). As illustrated in charts of Fig. 4, the structures of the BHL-WHN line have similar liquefaction susceptibilities as the average facilities in Fig. 3. In contrast, the structures of the Inter-Island show a decreased range of “high” (-11.1 %) and “very high” (-5.5 %) values, indicating they are less susceptible to liquefaction. This also applies to the transmission sites: While the substation in Whakamaru (BHL-WHN line) is very susceptible (“high”), Inter-Island sites result in mostly “very low” susceptibilities (except for the power cable terminal in Oteranga Bay, Wellington).

Based on the susceptibility results alone, the BHL-WHN line appears to carry a greater risk. However, it is located in an area where strong earthquakes are unlikely. For the Inter-Island, on the other hand, the likelihood of ground shaking is considered high due to its proximity to a number of active fault sources (Stirling et al., 2012). Therefore, by taking both these factors into account, liquefaction-induced damages are more likely to occur to the Inter-Island line.

The example illustrates that the assessment of the susceptibility map alone will lead to incorrect outcomes. The inclusion of ground motion data for different earthquake scenarios and seismic hazard estimates is indispensable for a proper analysis of the liquefaction hazard.

4.2 Infrastructure criticality

Partially or fully damaged infrastructure can cause a diversity of consequences on the economy and society. Some networks are more relevant than others, making infrastructure significance or criticality an important factor for the evaluation of the potential impact of liquefaction induced damage. This will be demonstrated by comparing two state highways on the South Island, which may both exposed to an Alpine fault earthquake: (1) SH1, which starts in Picton and runs down the East coast to Bluff while passing several sea ports and dense populated areas, such as Christchurch and Dunedin; (2) SH6, which starts in Blenheim crossing over to Westport and running south along the West Coast. After Haast, the SH6 turns away from the coast to pass Queenstown and to find its final destination in Invercargill. Fig. 5 presents the liquefaction

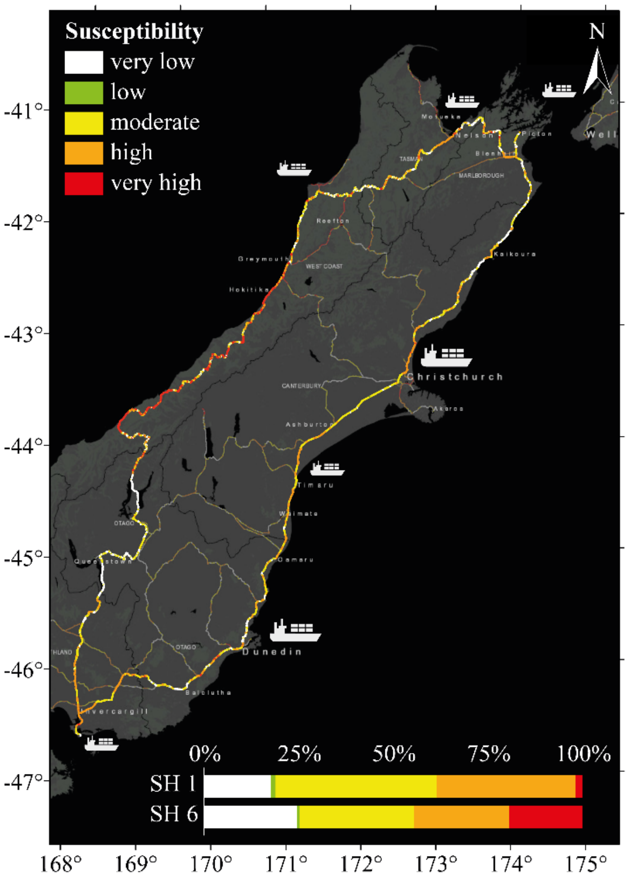

Fig. 5 Liquefaction susceptibility of state highway SH1 (East) and SH6 (West)

susceptibility of both state highways incl. the locations of sea ports on the South Island. While SH1 appears to have a nearly homogenous distribution, SH6 shows a cluster of "very high" susceptibilities within the West Coast area. The differences are also illustrated in the charts: Compared to the results in Fig. 3, the range of "high" susceptibilities increased for SH1 (+7.2 %), while the number of "very high" susceptibilities dropped considerably (-6.9 %). SH6 clearly stands out in the category "very high": Around 20 % of the highway are very susceptible to liquefaction.

The comparison of both state highways indicates that attention should be paid to the critical section of SH6 along the West Coast. However, in terms of infrastructure criticality, it becomes clear that SH1 has a strikingly higher traffic volume (in parts more than 10 000 vehicles per day) and links the majority of sea ports to the national transport system (Ministry of Transport, 2011). Therefore, although the liquefaction may be lower along SH1, the impact on national transportation and economy would likely be a lot more significant.

The example emphasizes the importance of infrastructure significance and criticality during a hazard assessment. This requires a proper understanding of the diverse and complex factors contributing to a network's economic and social value.

5 CONCLUSION

The geospatial model of Zhu et al. (2017) provided a useful tool to develop a national-scale liquefaction susceptibility map of New Zealand. Infrastructure for transportation and power was integrated to the map, showing that (1) state highways and rail lead to similar susceptibility results due to their common location, (2) bridges are more susceptible than other structures, because they are often located adjacent to rivers, and (3) transmission sites and structures are less susceptible to liquefaction than transportation networks as they are often situated across hills and away from alluvial deposits or coasts.

The comparison of different networks, discussed in 4.1 and 4.2, underlines the fact that creating a national-scale susceptibility map is only the first step to an adequate liquefaction assessment. Comprehensive data on ground shaking and methods to measure infrastructure criticality are required to fully understand the potential impacts of infrastructure networks that are exposed to liquefaction.

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